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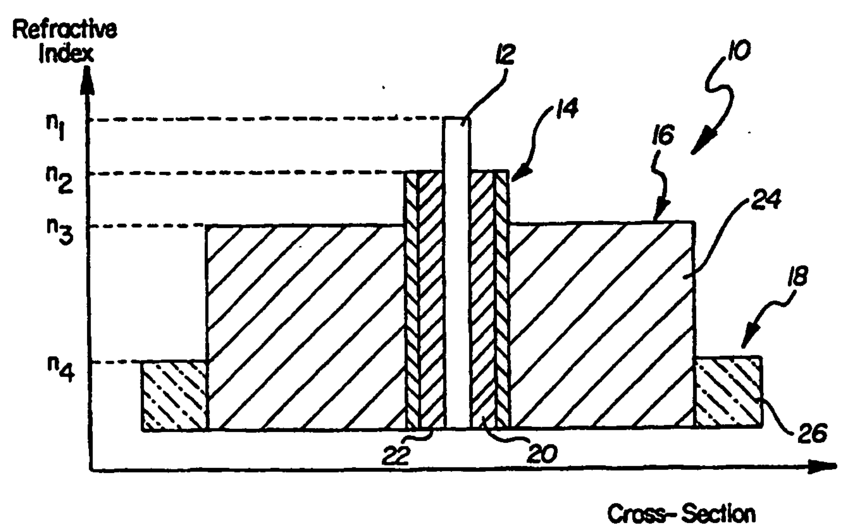


(57) Abstract

An optical fiber (10) made with a central core (12), a first cladding layer (16), and a second cladding layer (18) having a series of perturbations or irregularities formed into the otherwise generally circular outer boundary of the first cladding layer. The irregularities in the first cladding layer interrupt the propagation of skew rays and encourage coupling into the core. The irregularities are formed by drilling holes (44-58) in the fiber preform, which are parallel with its longitudinal axis, and inserting rods therein. An intermediate cladding layer (14) is provided for suppressing higher order core modes. The optical fibers are used in cladding pumped fiber lasers and amplifiers.

Ansprüche

What is claimed is:
CLAIMS
1. A optical fiber comprising:
a core region formed of a doped glass material, said core region adapted to absorb radiation at a first wavelength and provide gain at a second wavelength;
a first cladding layer having an outer boundary, and disposed around said core region, said first cladding layer having a plurality of irregularities found at least along said outer boundary; and
a second cladding layer having an inner and outer boundary, said inner boundary conforming to the outer boundary of said first cladding layer.

2. An optical fiber as in claim 1, wherein said core region is doped with an element selected from the group of Ce, Yb, Er, P, and combinations thereof.

3. An optical fiber as in claim 1, wherein said first cladding layer is fabricated of glass.

4. An optical fiber as in claim 3, wherein said glass is a doped or undoped silica glass.

5. An optical fiber as in claim 1, wherein said irregularities interrupt the propagation of radiation entering said first cladding layer.

6. An optical fiber as in claim 1, wherein said outer boundary of said first cladding layer is a radically constrained, non-circular outer boundary.

7. An optical fiber as in claim 1, wherein said irregularities are a series of protrusions extending away from said core region.

8. An optical fiber as in claim 7, wherein said protrusions are a plurality of semi-circular protrusions.

9. An optical fiber as in claim 1, wherein said irregularities are a series of stressed regions introduced into said first cladding layer.

10. An optical fiber as in claim 1, further comprises an intermediate cladding layer between said core region and said first cladding layer.

11. An optical fiber as in claim 10, wherein said intermediate cladding layer has a different refractive index than that of said core region.

12. An optical fiber as in claim 11, wherein said intermediate cladding layer is adapted to eliminate unwanted modes in said radiation.

13. An optical fiber as in claim 11, wherein said intermediate cladding layer comprises a plurality of sub-layers.

14. An optical fiber as in claim 13, wherein a first sub-layer is adapted to propagate radiation along said core region, and a second sub-layer is adapted to eliminate unwanted modes in said radiation.

15. An optical fiber comprising:
a centrally disposed core region adapted to absorb radiation at a first wavelength and provide gain at a second wavelength, said radiation having at least one mode;
an intermediate cladding layer disposed around said core region, said intermediate cladding layer eliminating modes in said radiation
a first cladding layer having an outer boundary and disposed around said intermediate cladding layer, said first cladding layer having a plurality of irregularities formed at least along said outer boundary; and
a second cladding layer disposed around said first cladding layer.

16. An optical fiber as in claim 15, wherein said core region is doped with an element selected from the group of Ce, Yb, Er, P, and combinations thereof.

17. An optical fiber as in claim 15, wherein said first cladding layer is fabricated of glass.

18. An optical fiber as in claim 17, wherein said glass is a doped or undoped silica glass.

19. An optical fiber as in claim 15, wherein said irregularities interrupt the propagation of radiation entering said first cladding layer.

20. An optical fiber as in claim 15, wherein said outer boundary of said first cladding layer is a radically constrained, non-circular outer boundary.

21. An optical fiber as in claim 15, wherein said irregularities are a series of protrusions extending away from said core region.

22. An optical fiber as in claim 21, wherein said protrusions are a plurality of semi-circular protrusions.

23. An optical fiber as in claim 15, wherein said irregularities are a series of stressed regions introduced into said first cladding layer.

24. An optical fiber as in claim 15, wherein said intermediate cladding layer has a different refraction index than that of said core region.

25. An optical fiber as in claim 15, wherein said intermediate cladding layer comprises a plurality of sub-layers.

26. An optical fiber as in claim 25, wherein a first sub-layer is adapted to propagate radiation along said core region, and a second sub-layer is adapted to eliminate unwanted modes in said radiation.

27. An optical fiber comprising:
a central core region adapted to absorb radiation at a first wavelength and provide gain at a second wavelength, said radiation having at least one mode;
an intermediate cladding layer disposed around said core region, said intermediate cladding layer having a plurality of sub-layers;
a first cladding layer having a radically constrained, non-circular outer boundary, and disposed around said intermediate cladding layer; and
a second cladding layer disposed around said first cladding layer.

28. An optical fiber as in claim 27, wherein said core region is doped with an element selected from the group of Ce, Yb, Er, P, and combinations thereof.

29. An optical fiber as in claim 27, wherein said glass is a doped or undoped silica glass.

30. An optical fiber as in claim 27, wherein said protrusions are a plurality of semi-circular protrusions.

31. An optical fiber as in claim 27, wherein said intermediate cladding layer has a different refractive index than that of said core region.

32. An optical fiber as in claim 27, wherein a first sub-layer is adapted to propagate radiation along said core region, and a second sub-layer is adapted to eliminate unwanted modes in said radiation.

Beschreibung

DOUBLE-CLAD RARE EARTH DOPED OPTICAL FIBERS
FIELD OF THE INVENTION
The instant invention relates to double clad optical fiber optimized for use in, for example, fiber lasers and amplifiers, as well as methods of manufacture and uses therefor.

BACKGROUND OF THE TECHNOLOGY
Optical amplifiers, and in particular the optically-pumped erbium doped fiber amplifier (EDFA), are widely used in fiberoptic transmission systems (see, for example, E. Desurvire, Erbium Doped Fiber Amplifiers,
Wiley, New York, 1994). In a typical device, a weak 1550 nanometer (nm) optical signal and a strong 980 nm pump signal, both propagating in singlemode optical fiber, are combined by means of a fused dichroic coupler into one single-mode fiber. This fiber is then coupled to a single-mode erbium-doped fiber where the erbium ions absorb the pump radiation and provide gain at the signal wavelength. The result is that the output of the EDFA is an amplified replica of the input signal. Such amplifiers are useful for overcoming the various losses that occur an any fiberoptic transmission system.

In a conventional fiber amplifier, the pump source consists of a laser diode operating in a single transverse mode coupled to single-mode optical fiber. The amount of optical power that can be obtained from such devices is limited by the power density at the output facet of the pump laser. To increase the diode output power, it is necessary to increase the emitting area of the diode. Unfortunately, when this is done, the transverse mode structure of the resulting broad area laser becomes multimode, and the laser output is no longer sufficiently coherent to be coupled into a single-mode fiber. Such a diode output can, however, be coupled into a multimode fiber, to provide an essentially incoherent source for pumping the amplifier. Such multimode fibers are typically round, since this shape is easier to fabricate than any alternative shape.

In a variation of this design, ytterbium may be added to the fiber (as taught in, for example, US patent no. 5,225,925, to Grubb, et al. issued Jul. 6.

1993). In the optimized fiber disclosed in the '925 patent, energy absorbed by the ytterbium ions is efficiently transferred to the erbium ions. This results in a fiber with a much stronger, broader absorption than can be obtained in a singly-doped erbium fiber. An amplifier made from such fiber (a ytterbiumerbium doped fiber amplifier or YEDFA), can be pumped with longer wavelength sources, such as a diode-pumped neodymium laser (see Grubb, et al. Electronics Letters, 1991);-output powers in excess of 4 watts (w) have been reported (Grubb, et al. paper TuG4 OFC 1996). The wavelengths of neodymium lasers used for this purpose has varied from 1064 nm in Nd:YAG to 1047 nm in Nd:YLF. Over this range in a typical fiber, the Yb absorption varies from 2 to 7 dB/m. For comparison, in the same fiber at 950 nm the absorption was 420 dB/m and at 975 nm it was 2500 dB/m.

Techniques also exist for pumping an amplifier directly with multimode diodes. US patent no. 3,808,549, issued April 30, 1974, to Mauer discloses a design in which a small, strongly absorbing, single-mode core is embedded in a large, multimode waveguide. With all modes excited, the optical power density in such a double clad wave guide is nearly uniform across the wave guide aperture. Under these conditions, the average absorption coefficient is approximately equal to the absorption coefficient of the core, normalized by the area ratio of the two waveguides. Radiation propagating in modes that overlap the doped region will be preferentially absorbed, and some form of mode mixing is often required to maintain the uniform power distribution required to ensure that all the power in the multimode wave guide will eventually be absorbed by the core.

Using a double clad design of this type, Minelly, et al. (IEEE Photonics
Technology Letters, 5(3), 301-303, 1993) demonstrated a YEDFA pumped with a broad area laser diode. Minelly, et al. used bulk optics to couple the output of a laser diode array to the double-clad fiber, and geometries using fused or reflective couplers similar to those used for conventional single-mode amplifiers can also be used. With some modification, for example, the filter wavelength division multiplexer (FWDM) made by E-Tek Dynamics Inc. of
San Jos CA could be used as a multimode coupler. This, combined with a double clad gain fiber would permit a multimode-pumped amplifier to be built in th same geom try as the conventional EDFA described above.

The fiber shown by Mauer was round with a concentric core, as was the fiber used by Minelly, et al.

This is a very inefficient shape for a double clad device. As noted by Snitzer et al. (US patent nos. 3,729,690, April 24, 1973 and 4,815,079, March 21, 1989), in a double clad fiber with radial symmetry, many of the modes in the multimode wav guide do not interact with, and are not absorbed by a concentric core. This phenomenon can also be described by geometrical optics, where it would be observed that the vast majority of the guided rays are skew rays that never pass through the core. This problem is a result of radial symmetry, and can be eliminated by perturbations that break this symmetry. Snitzer et al. proposed the use of an off-center, circular wave guide as well as a rectangular guide with two different transverse dimensions. Additionally, Lewis, et al. in US Patent No. 5,418,880 and Muendel in US Patent No. 5,533,163 teach the use of various space filling polygons. Such shapes are limited to triangles, certain symmetric quadrilaterals and regular hexagons.

The techniques used to make fibers with these shapes generally resulted in polymer-clad fibers that were not round or which had a singlemode core that was not concentric with the fiber. Polymer-clad fibers are less stable thermally and mechanically than silica fibers, and they can be easily damaged by the pump radiation. Non-concentric fibers are difficult to align and splice. The fact that the fibers are not round makes it difficult to combine these fibers with more standard fiber components, and to exploit the existing infrastructure of tools such as fiber cleavers, splicers and ferrules that are optimized for use round optical fibers. For practical applications, it is important to utilize a shape that can be surrounded by a thickness of lowindex silica outer cladding with a round outer diameter. Typical 100/125 multimode fiber has a 12.5 micron (pm) cladding thickness. The maximum outer radius of the wave guide is constrained by the desired outer diameter minus the cladding thickness.

Multimode pump sources and couplers are also optimized for round fiber. To efficiently couple a round multimode pump fiber to a non-circular gain fiber, it is important that the pump fiber diameter be less than or equal to the minimum inner diameter of the low-index silica outer cladding. Any radial perturbation in such fibers will be constrained to an annular region whose inner diameter is limited by the pump fiber diameter and whose outer diameter is limited by the fiber outer diameter and cladding thickness. The constraints on actual fibers are such that the radial dimension of the wave guide can only vary by +10%, with values as small as +5% being preferable in some cases. There is therefore a need for fibers that appear externally as round, concentric, all-silica fibers, but which nonetheless have been sufficiently perturbed to allow efficient double-clad absorption to occur.

Finally, it is important to recognize that double clad fibers are not truly single mode fibers. The same perturbations that allow efficient absorption also ensure that many guided modes at the signal wavelength will have appreciable overlap with the fiber core. This is often not a problem in a fiber laser, because the modes that oscillate will be those that most efficiently overlap the core region. However, in an amplifier, signal power that is coupled into the multimode wave guide could give rise to signal distortions when this signal is accidentally amplified and coupled back into the output signal. There is clearly a need for fibers that prevent these parasitic processes from occurring.

Accordingly, there exists a need for enhanced optical fibers in which guided rays propagating along the length of the fiber are passed through the fiber core. The enhanced fiber should retain the preferred round shape to remain compatible with other fiber components, as noted above. Likewise, the core of the fiber should preferably be substantially in the center of the fiber.

SUMMARY OF THE INVENTION

It is an object of the invention to provide a double-clad optical fiber structure that allows pump radiation propagating in a multimode wave guide to be absorbed into a single-mode core.

It is another object of the invention to provide a double-clad optical fiber structure that allows amplification of optical signals propagating in the fundamental mode of the structure while suppressing parasitic amplification of other modes.

In accordance with these and other objects of the invention that will become apparent from the description herein, an optical fiber coupler comprises: a central glass core, doped to absorb radiation at a pump wavelength and to provide gain at a signal wavelength, a first glass cladding layer that, at the pump wavelength, is transparent and that, at the signal wavelength, optimizes coupling and amplification for the fundamental mode while minimizing coupling and amplification for other modes, and a second glass cladding layer with a noncircular outer boundary that is still near enough to round and concentric that a round outer cladding is possible.

The fiber may include a third cladding layer, that has an inner boundary that conforms to the outer boundary of the second cladding and that has a round outer diameter.

A method for making the optical fiber coupler according to the invention includes a sequence of

procedures where the core and first cladding regions are fabricated using MCVD and solution doping in a fused silica preform, the non-circular interface between the second and third claddings is obtained by inserting a series of rods into holes drilled at the core-cladding interface of a silica preform with a fluorosilicate outer cladding layer, and a final preform is prepared by inserting the first preform into a hole in the second preform that is concentric with its out r diamet r.

The fiber of the present invention is sufficiently asymmetric that it allows radiation propagating in the multimode wave guide to be efficiently absorbed in the core, yet sufficiently symmetric that it can be handled like conventional round fiber.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross sectional illustration of an optical fiber having a core and three claddings, in accordance with the present invention;
FIG. 2 illustrates the propagation of light rays in a conventional round optical fiber; and
FIG's. 3a - 3c are a series of cross sectional illustrations demonstrating steps for producing a noncircular wave guide embedded in a round glass fiber.

DETAILED DESCRIPTION OF THE INVENTION

While the specification concludes with claims defining the features of the invention that are regarded as novel, it is believed that the invention will be better understood from a consideration of the following description in conjunction with the drawing figures, in which like reference numerals are carried forward.

A conventional all-silica double-clad fiber consists of a doped core with a diameter less than 10 pm and a numerical aperture greater than 0.10, surrounded by a fused silica multimode wave guide with a diameter near 100 pm with a numerical aperture (n) of 0.22, defined by an outer cladding of fluorine doped silica with n = silica - .017.

In the case of YbEr fibers, the optimum area for the multimode wave guide depends on the pump wavelength and the desired performance.

For 1047 nm-like performance with a 950 nm pump the area ratio would have to be 60. For 1064 nm-like performance with a 975 nm pump an area ratio of 1250 would be acceptable. A typical value of 100 is consistent with typical pump diodes, single-mode core diameters, and multimode fiber numerical apertures. For example, the core diameter of a typical single-mode fiber at 1550 nm (Corning SMF-28) is 8.3 clam, leading to a multimode waveguide diameter of 83 mm. A typical 1 Watt (W) laser diode has an aperture of 100 mm and a numerical aperture of 0.13; assuming a (typical) silica multimode fiber numerical aperture of 0.22, this can be focused into a 60 pm fiber. The difference between 60 pm and 83 pm can be used to accommodate any mechanical tolerances and aberrations in the coupling optics.

The choice of core size is dependent upon which one of many attributes one wishes to emphasize in a particular application. In low power amplifiers, it is usually desirable to minimize the core diameter, D, in order to reduce the saturation power to the lowest possible value. This maximizes efficiency and allows the amplifier to operate with low input powers. In a high power amplifier, particularly one used for video applications, the input signal is usually much larger than the amplifier saturation power, and the issue of core size is less important. In fact, it is often desirable to maximize the core size to reduce the possibility of optical damage or to simplify splicing to conventional fibers. The optimum core size is then limited by the bending losses associated with large, low numerical aperture (NA) fibers. Since this is the same issue that determines optimum core sizes in standard telecommunication fiber, it appears that a similar fiber size (e.g. D = 8.3 plm and a 0.12 NA for SMF-28) would be optimal. In the case of double clad amplifiers, maximizing the doped core area maximizes the allowable size of the multimode wave guide, which in turn allows the use of larger, more powerful pump diodes, or less demanding alignment tolerances.

To maximize the diameter of the doped core, it is necessary to maximize the diameter of the fundamental mode. In ordinary single mode fiber, this is done by making a larger core with a smaller numerical aperture.

The usual way of doing this is to reduce the refractive index of the core.

Unfortunately, in Yb Er co-doped fibers, the refractive index of the core is fixed at nl = silica + .013 by the phosphorous and rare earth doping requirements. With a silica cladding, this gives a numerical aperture of approximately 0.20, resulting in a singl mode waveguid diameter of 5.5 pm for cutoff at 1450 nm. In principle, the numerical aperture can be reduced by increasing the cladding refractive index. Decreasing th NA to a value of 0.12 would require a cladding ind x of n2 = silica + .008. In a typical geom try, wh re the core is prepared by modified chemical vapor deposition (MCVD) and

solution doping, this would suggest the use of a doped starting tub with a larger-than-normal refractive index. Unfortunately, such starting tubes are not readily available, so such an approach is not immediately practical.

A more practical alternative for increasing the core area is to consider a multilayer core configuration. Referring now to FIG. 1, there is illustrated therein a cross-sectional vi w of an optical fiber 10 having a core 12, and three claddings 14, 16, and 18 respectively. Each of the core and respective claddings will be discussed in greater detail below. As illustrated in FIG. 1, a layer of doped material corresponding to cladding 14 may be deposited between cladding 16, such as a silica starting tube, and the YbEr doped core 12. If this layer of doped material is thick enough, and is fabricated of the right materials, then the properties of the fundamental radiation mode will be determined only by the core index and the surrounding index pedestal.

More particularly, the core 12 may be fabricated of any of a number of core materials known in the art, preferred materials being Yb-Er doped optical fibers which may further include a doping material such as phosphorous and/or cesium, among others. The first cladding region 14, also referred to as the pedestal, is as described above, one or more layers of doped material. For example, cladding 14 may include a first doped layer 20 and a second doped layer 22. One preferred function of the first cladding 14 is to have a higher index of refraction than the silica starting tube (cladding 16), though less than the core 12. As such, layer 22 may be fabricated of any one or more materials well known in the art, an example of which is germanium.

Layer 20 may likewise have a reflective property or may be adapted to perform other functions. Hence, in FIG. 1, layer 20 may be fabricated of a material which absorbs or strips undesirable modes of light. Accordingly, layer 20 may be fabricated of a cobalt containing material. Other functions (and materials) may be employed as both layers 20 and 22. Moreover, it is important to note that cladding 14 may also be eliminated in certain applications.

Disposed about cladding 14 is second cladding 16, which is typically fabricated of a layer of pure or modified silica material 24, or other material as is well known in the art. The third cladding layer 18 is disposed about the outside of the second cladding layer 16, and is typically fabricated of a fluorine doped silica material 26, and is the outer covering for the optical fiber.

Typical refraction index profiles for the core and claddings are also shown in FIG. 1, and below.

CORE Cladding 14 Cladding 16 Cladding 18
Diameter in
8.3 8.3 20 90 125
Refractive
Indices 1.457 1.453 1.444 1.427

The optical modes typical of the structure of FIG. 1 can be calculated from the usual Bessel functions, and the effective indices and power densities can be calculated for each mode. The modes can be labeled by their effective indices as core modes (ni > neff > n2), pedestal modes (n2 > neff > n3), and wave guide modes (n3 > neff > n4). The latter two groups are collectively referred to as cladding modes.

Table 1 gives the effective indices and the distribution of the modal power or modes (HE) in both the core and pedestal modes, as well as the region defined by layer 20. The fraction of the power in this region can be used to estimate how losses in this region will affect the various modes.

Table 1
Properties of the core and pedestal modes at
1550 nm for the fiber shown in FIG. 1.

FIG-1

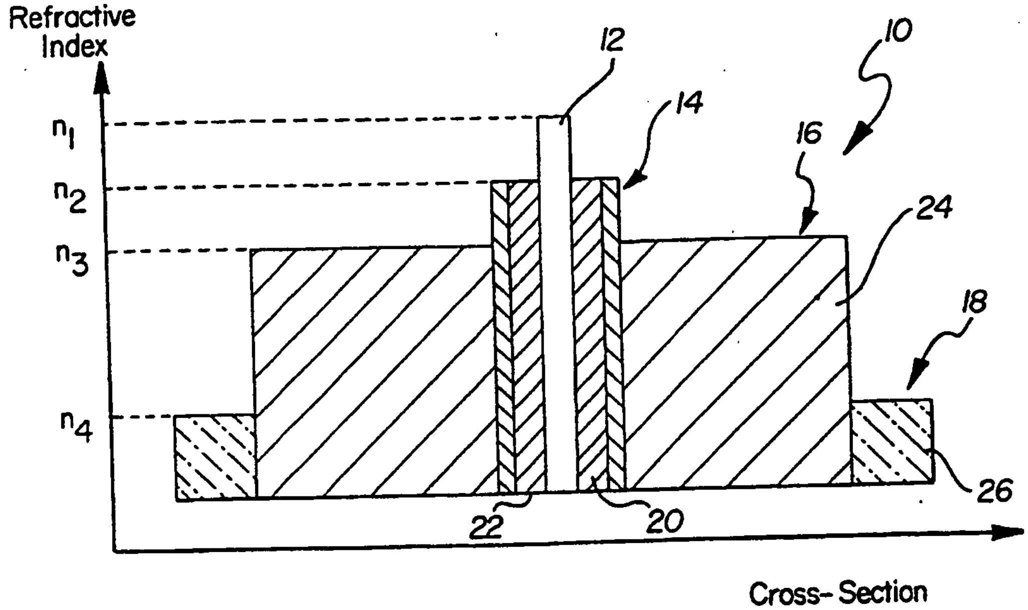

Refractive Index
12
10
14
16
24
18
26
20
22
Cross-Section

FIG-2A

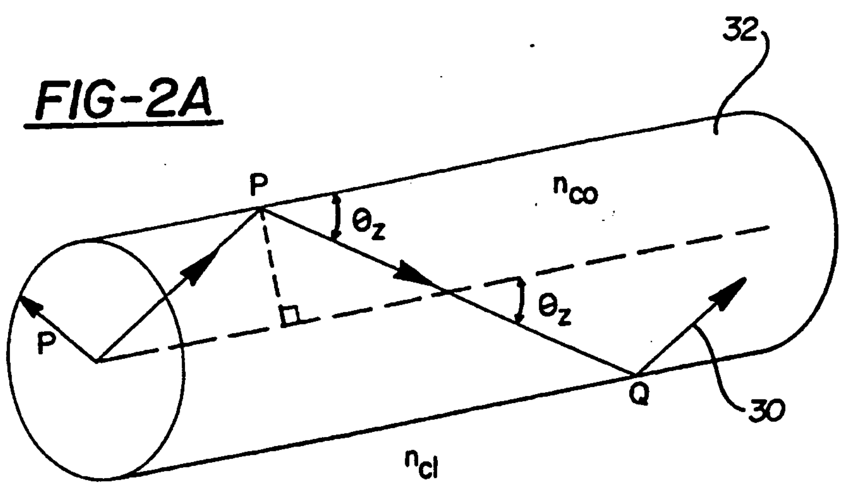

32
P
P
Q
30
n_{co}
n_{cl}
θ_z
θ_z

FIG-2B

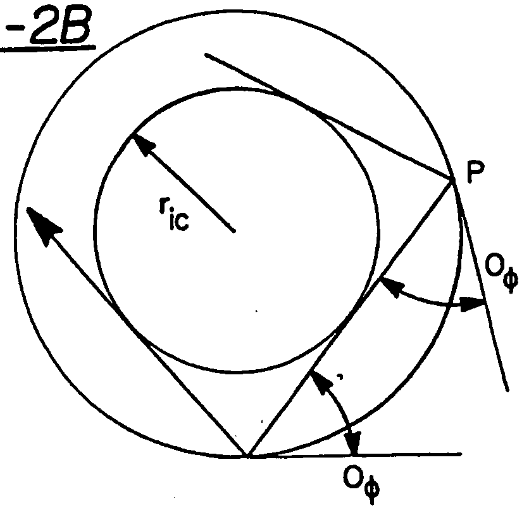


FIG-3A

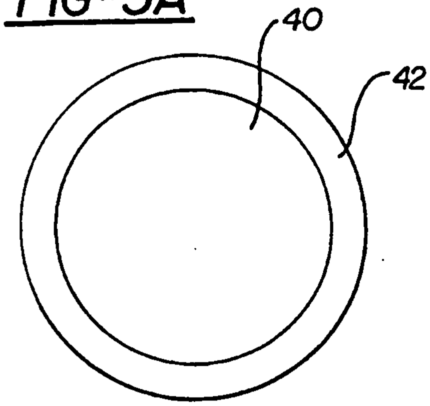
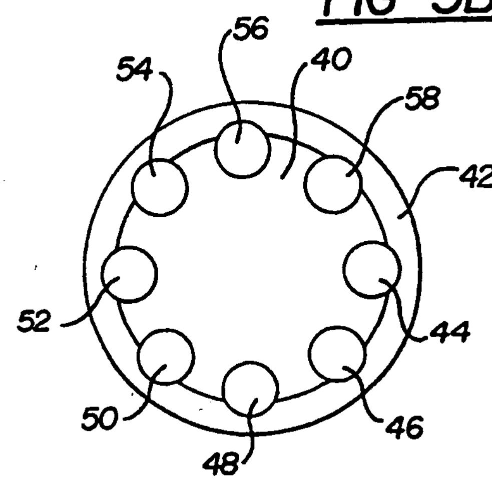


FIG-3B



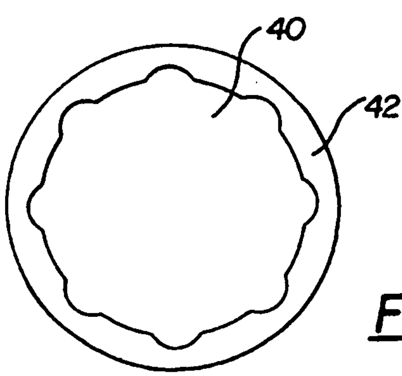


FIG-3C

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